

Top quark pair production via (un)polarized photon collisions in the littlest Higgs model with T-parity at the ILC

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Abstract

We study the top-quark pair production via polarized and unpolarized photon collisions at the International Linear Collider in the context of the littlest Higgs model with T-parity. We calculate the production cross section of the process $\gamma\gamma \rightarrow t\bar{t}$ and find the effects can be more significant in the $--$ polarized photon collision mode than in other collision modes, and the relative correction can be expected to reach about -1% in the favorable parameter space.

PACS numbers: 14.65.Ha, 12.15.Lk, 12.60.-i, 13.85.Lg

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I. INTRODUCTION

The detailed analysis of the dynamics of top-quark production and decay is a major objective of experiments at the Tevatron, the Large Hadron Collider(LHC), and a possible International Linear Collider(ILC). Top quarks can be produced at hadron colliders via top-antitop pair [1] and single top [2] production channels. For top-pair production, the leading-order (LO) partonic processes are $q\bar{q} \rightarrow t\bar{t}$, which is dominant at Tevatron energies, and $gg \rightarrow t\bar{t}$, dominant at LHC energies. At the ILC, one of the most important reactions will be top-pair production well above the threshold. Because of the small statistics, the top-quark properties have not been precisely measured at the Tevatron. Several tens of millions of top pair signals per year will be produced at the LHC, this large number of top quarks allow very precise measurements in the top-quark properties. Compared to the LHC, the $t\bar{t}$ production cross section is less at the ILC[3], but it will be an ideal place for further investigating the top quark duo to its clean background.

The little Higgs theory constructs the Higgs as a Pseudogoldstone boson to solve the hierarchy problem of the Standard Model(SM)[4]. The littlest Higgs (LH) model [5] is an economical approach to implement this idea, but electroweak precision tests give it strong constraints [6] so that the fine-tuning problem in the Higgs potential would be reintroduced[7]. Then, a discrete symmetry called T-parity is proposed to tackle this problem[8], this resulting model is referred to as the littlest Higgs model with T-parity (LHT).

The LHT model predicts new particles, such as T-odd gauge bosons and T-odd fermions. In the LHT model, there are interactions between the SM fermions and the mirror fermions mediated by the new T-odd gauge bosons or T-odd Goldstone bosons. These interactions can contribute to the $\gamma t\bar{t}$ coupling and the production cross section of the process $\gamma\gamma \rightarrow t\bar{t}$. Furthermore, an additional heavy quark T^+ and its partner T^- can also contribute to the $\gamma t\bar{t}$ coupling. In this paper, we will study the polarized and unpolarized $\gamma\gamma$ collisions in the LHT model at the ILC.

This paper is organized as follows. In Sec.II we give a brief review of the LHT model. In Sec.III and IV we respectively calculate the one-loop contributions of the LHT model to the $\gamma\gamma \rightarrow t\bar{t}$ in polarized and unpolarized photon-photon collision modes and show some numerical results at the ILC. Finally, we give our conclusions in Sec.V.

II. A BRIEF REVIEW OF THE LHT MODEL

The LHT model [8] is based on an $SU(5)/SO(5)$ non-linear sigma model, where with the global group $SU(5)$ being spontaneously broken into $SO(5)$ by a 5×5 symmetric tensor at the scale $f \sim \mathcal{O}(TeV)$, the gauged subgroup $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$ of $SU(5)$ is broken to the diagonal subgroup $SU(2)_L \times U(1)_Y$ of $SO(5)$.

From the symmetry breaking, there arise 4 new heavy gauge bosons W_H^\pm, Z_H, A_H whose masses up to $\mathcal{O}(v^2/f^2)$ are given by

$$M_{W_H} = M_{Z_H} = gf(1 - \frac{v^2}{8f^2}), M_{A_H} = \frac{g'f}{\sqrt{5}}(1 - \frac{5v^2}{8f^2}) \quad (1)$$

with g and g' being the SM $SU(2)$ and $U(1)$ gauge couplings, respectively.

A consistent viable implementation of T-parity in the fermion sector requires the introduction of mirror fermions. For each SM quark, a copy of mirror quark with T-odd quantum number is added. We denote up-type and down-type mirror quarks by u_H^i, d_H^i respectively, where $i = 1, 2, 3$ are the generation index, whose masses up to $\mathcal{O}(v^2/f^2)$ are given by

$$m_{d_H^i} = \sqrt{2}\kappa_i f, m_{u_H^i} = m_{d_H^i}(1 - \frac{v^2}{8f^2}) \quad (2)$$

where κ_i are the diagonalized Yukawa couplings of the mirror quarks.

An additional heavy quark T^+ is introduced to cancel the large contributions to the Higgs mass from one-loop quadratic divergences. The implementation of T-parity then requires also a T-odd partner T^- , which is an exact singlet under $SU(2)_1 \times SU(2)_2$. Their masses up to $\mathcal{O}(v^2/f^2)$ are given by

$$m_{T^+} = \frac{f}{v} \frac{m_t}{\sqrt{x_L(1-x_L)}} [1 + \frac{v^2}{f^2} (\frac{1}{3} - x_L(1-x_L))] \quad (3)$$

$$m_{T^-} = \frac{f}{v} \frac{m_t}{\sqrt{x_L}} [1 + \frac{v^2}{f^2} (\frac{1}{3} - \frac{1}{2}x_L(1-x_L))] \quad (4)$$

where x_L is the mixing parameter between the SM top-quark t and the heavy quark T^+ .

In the LHT model, one of the important ingredients of the mirror sector is the existence of four CKM-like unitary mixing matrices, two for mirror quarks and two for mirror leptons:

$$V_{Hu}, V_{Hd}, V_{Hl}, V_{H\nu} \quad (5)$$

where V_{Hu} and V_{Hd} are for the mirror quarks which are present in our analysis. They satisfy the relation $V_{Hu}^\dagger V_{Hd} = V_{CKM}$. We follow Ref.[9] to parameterize V_{Hd} with three angles $\theta_{12}^d, \theta_{23}^d, \theta_{13}^d$ and three phases $\delta_{12}^d, \delta_{23}^d, \delta_{13}^d$

$$V_{Hd} = \begin{pmatrix} c_{12}^d c_{13}^d & s_{12}^d c_{13}^d e^{-i\delta_{12}^d} & s_{13}^d e^{-i\delta_{13}^d} \\ -s_{12}^d c_{23}^d e^{i\delta_{12}^d} - c_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{23}^d)} & c_{12}^d c_{23}^d - s_{12}^d s_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d - \delta_{23}^d)} & s_{23}^d c_{13}^d e^{-i\delta_{23}^d} \\ s_{12}^d s_{23}^d e^{i(\delta_{12}^d + \delta_{23}^d)} - c_{12}^d c_{23}^d s_{13}^d e^{i\delta_{13}^d} & -c_{12}^d s_{23}^d e^{i\delta_{23}^d} - s_{12}^d c_{23}^d s_{13}^d e^{i(\delta_{13}^d - \delta_{12}^d)} & c_{23}^d c_{13}^d \end{pmatrix} \quad (6)$$

III. TOP QUARK PAIR PRODUCTION VIA $\gamma\gamma$ COLLISION IN THE LHT MODEL

In the context of the LHT model, the relevant Feynman diagrams of the one-loop correction to the process $\gamma\gamma \rightarrow t\bar{t}$ are shown in Fig.1, where the black dot represents the effective $\gamma t\bar{t}$ vertex which is shown in Fig.2 and the black diamond represents the fermion propagator.

In our calculation, the higher order couplings between the scalar triplet Φ and top quark and the high order $\mathcal{O}(v^2/f^2)$ terms in the masses of new particles and in the Feynman rules are neglected. The relevant Feynman rules can be found in Ref.[10]. We use the 't Hooft-Feynman gauge, so the masses of the Goldstone bosons and the ghost fields are the same as their corresponding gauge bosons. The ultraviolet divergences have been regulated by the dimensional regularization scheme and the divergences have been canceled according to the on-shell renormalization scheme.

For the $\gamma\gamma$ collision at the ILC, the photon beams are generated by the backward Compton scattering of incident electron- and laser-beams just before the interaction point. The total cross section $\sigma(s)$ for the top-pair production can be obtained by folding the elementary cross section $\hat{\sigma}(\hat{s})$ for the subprocess $\gamma\gamma \rightarrow t\bar{t}$ with the photon luminosity at the e^+e^- colliders given in Ref.[11]

$$\sigma(s) = \int_{2m_t/\sqrt{s}}^{x_{\max}} dz \frac{dL_{\gamma\gamma}}{dz} \hat{\sigma}(\hat{s}) \quad (\gamma\gamma \rightarrow t\bar{t} \text{ at } \hat{s} = z^2 s), \quad (7)$$

where \sqrt{s} and $\sqrt{\hat{s}}$ are the e^+e^- and $\gamma\gamma$ center-of-mass energies respectively, and $dL_{\gamma\gamma}/dz$ is the photon luminosity, which can be expressed as

$$\frac{dL_{\gamma\gamma}}{dz} = 2z \int_{z^2/x_{\max}}^{x_{\max}} \frac{dx}{x} F_{\gamma/e}(x) F_{\gamma/e}(z^2/x). \quad (8)$$

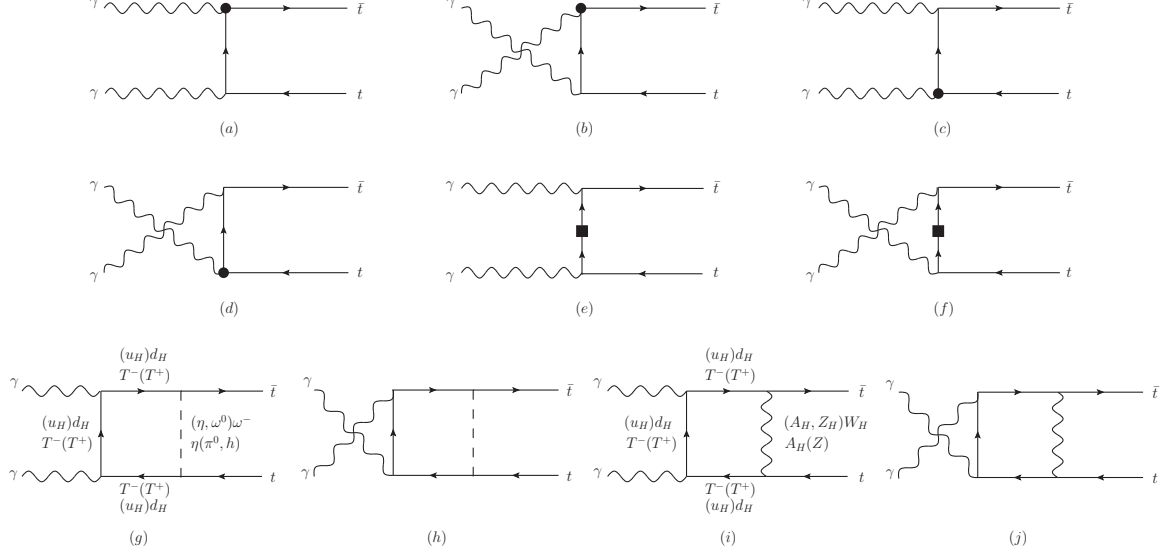


FIG. 1: Feynman diagrams of the one-loop correction to the process $\gamma\gamma \rightarrow t\bar{t}$ in the LHT model.

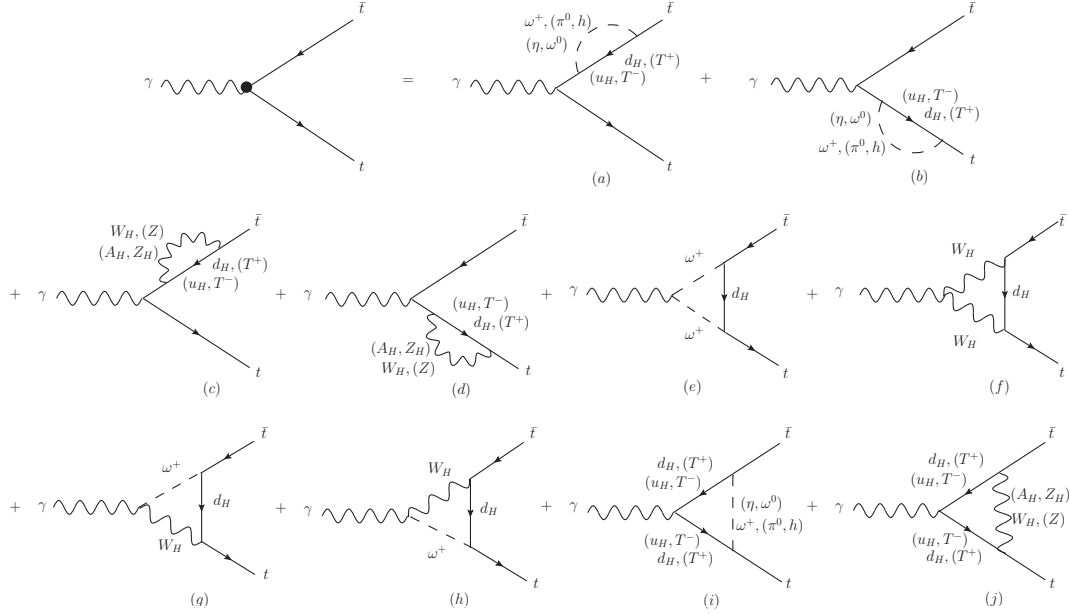


FIG. 2: The effective $\gamma t\bar{t}$ vertex diagrams at one-loop level in the LHT model.

For unpolarized initial electron and laser beams, the energy spectrum of the backscattered photon is given by

$$F_{\gamma/e}(x) = \frac{1}{D(\xi)} \left(1 - x + \frac{1}{1-x} - \frac{4x}{\xi(1-x)} + \frac{4x^2}{\xi^2(1-x)^2} \right). \quad (9)$$

where $\xi = 4E_e E_0 / m_e^2$ and E_e are respectively the incident electron mass and energy,

E_0 is the initial laser photon energy. In our numerical calculation, we choose $\xi = 4.8$, $D(\xi) = 1.83$ and $x_{max} = 0.83$.

The $\gamma\gamma$ collisions have five polarization modes as follows: $++$, $--$, $+-$, $-+$ and unpolarized collision modes, where the notation $+$ and $-$ represent the helicities of the two incoming photons being $\lambda_1 = 1$ and $\lambda_1 = -1$, respectively.

IV. NUMERICAL RESULTS

In our numerical calculations, we take the SM parameters as[12]

$$\begin{aligned} G_F &= 1.16637 \times 10^{-5} GeV^{-2}, \quad S_W^2 = \sin^2 \theta_W = 0.231, \\ \alpha_e &= 1/128, \quad M_{Z_L} = 91.2 GeV, \quad m_t = 172.4 GeV, \quad m_h = 120 GeV. \end{aligned} \quad (10)$$

The LHT parameters relevant to our study are the scale f , the mixing parameter x_L , the mirror quark masses and the parameters in the matrices V_{Hu}, V_{Hd} . For the mirror quark masses, we get $m_{u_H^i} = m_{d_H^i}$ at $\mathcal{O}(v/f)$ and further assume

$$m_{u_H^1} = m_{u_H^2} = m_{d_H^1} = m_{d_H^2} = M_{12}, m_{u_H^3} = m_{d_H^3} = M_3 \quad (11)$$

From the couplings between the mirror quarks and the heavy gauge bosons or the heavy Goldstone bosons, we can see the main contribution comes from the third family couplings. In order to show the largest correction, for the matrices V_{Hu}, V_{Hd} , we follow Ref.[13] to choose the following scenario: $V_{Hu} = 1, V_{Hd} = V_{CKM}$. In this scenario, the contribution of the LHT model comes entirely from the third family mirror quarks and the additional heavy quarks T^+, T^- .

In Fig.3(a), we discuss the dependance of the relative correction $\delta\sigma/\sigma$ on the center-of-mass energy \sqrt{s} . To see the influence of the scale f on the $\delta\sigma/\sigma$, we take $f = 500, 2000 GeV$, respectively. We can see $\delta\sigma/\sigma$ firstly decreases then increases with \sqrt{s} . The higher the scale f is taken, the shallower the curve becomes. To see the influence of the x_L on the $\delta\sigma/\sigma$, we take $x_L = 0.1, 0.7$, respectively. We can see that the larger the x_L is taken, the less the negative relative correction is generated. Furthermore, the larger the scale f is taken, the less influence the x_L can exert, which means the contributions of the T^+, T^- are suppressed by the high scale f . Considering the constraints of Ref.[14], the maximum of the relative correction can reach about -0.65% .

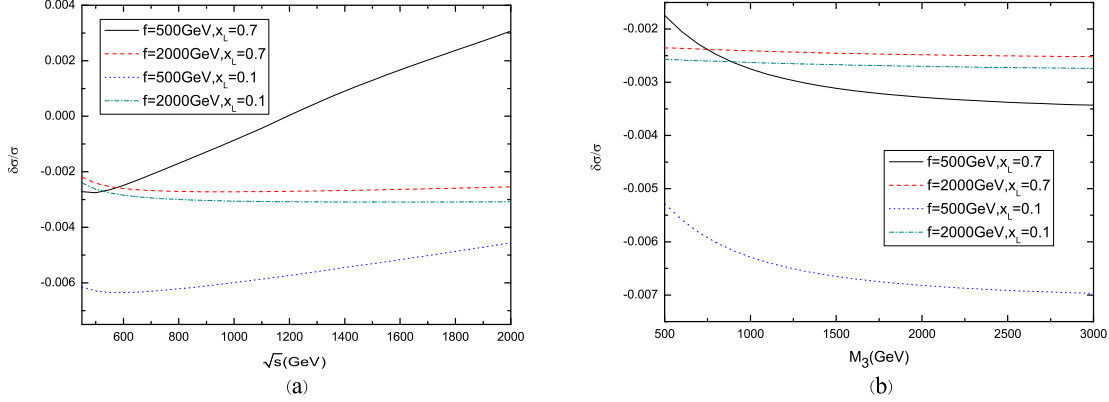


FIG. 3: The relative correction of the top-quark pair production cross section $\delta\sigma/\sigma$ as functions of the center-of-mass energy \sqrt{s} for $M_3 = 1000\text{GeV}$ (a) and the mirror quark mass M_3 for $\sqrt{s} = 500\text{GeV}$ (b) in unpolarized photon collision mode, respectively.

In Fig.3(b), we discuss the dependance of $\delta\sigma/\sigma$ on the third family mirror quark mass M_3 . We can see $\delta\sigma/\sigma$ is negative and becomes larger with the M_3 increasing. Same as above, we take $f = 500, 2000\text{GeV}$ respectively to see the influence of the scale f on the $\delta\sigma/\sigma$ and take $x_L = 0.1, 0.7$ respectively to see the influence of the x_L on the $\delta\sigma/\sigma$. The larger the scale f is taken, the shallower the curve becomes, which means the contributions of the T^+, T^- and the third family mirror quark are all suppressed by the high scale f . For the same x_L , the overall trend is that the higher the scale f is taken, the smaller the relative correction $\delta\sigma/\sigma$ is generated. For the same scale f , the larger the x_L is taken, the less the relative correction $\delta\sigma/\sigma$ is generated, which means $\delta\sigma/\sigma$ becomes less with the M_{T^+}, M_{T^-} increasing. Furthermore, we find the contribution of the third family mirror quark is negative while the contributions of the T^+, T^- change from negative to positive with the x_L from 0.1 to 0.7. For the case $f = 500\text{GeV}, x_L = 0.7$, the contributions of the T^+, T^- are positive so that they counteract the contribution of the third family mirror quark very strongly. As a result, the $\delta\sigma/\sigma$ for $f = 500\text{GeV}, x_L = 0.7$ is smaller than the case for $f = 2000\text{GeV}, x_L = 0.7$ when $M_3 < 750\text{GeV}$. For the case $f = 500\text{GeV}, x_L = 0.1$, the contributions of the T^+, T^- are negative so that the contribution of the third family mirror quark is enhanced obviously. The maximum of the relative correction can reach about -0.7% .

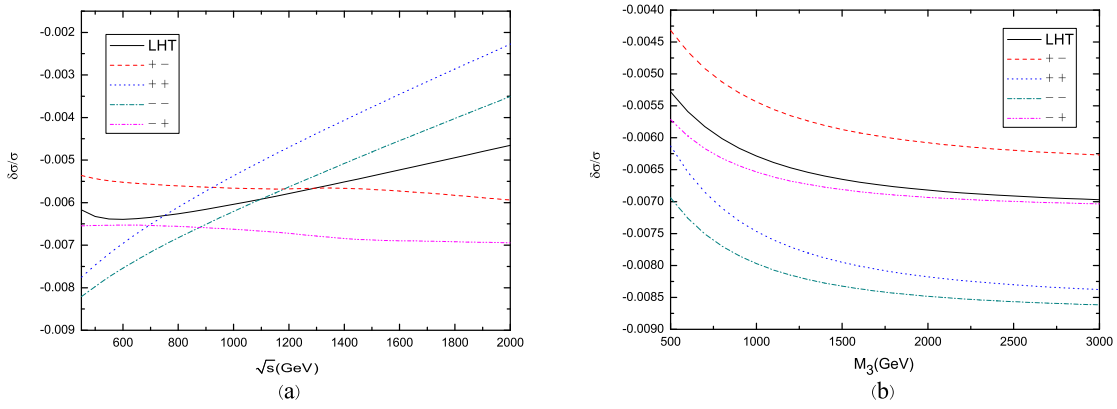


FIG. 4: The relative correction of the top-quark pair production cross section $\delta\sigma/\sigma$ as functions of the center-of-mass energy \sqrt{s} for $M_3 = 1000\text{GeV}$, $f = 500\text{GeV}$, $x_L = 0.1$ (a) and the mirror quark mass M_3 for $\sqrt{s} = 500\text{GeV}$, $f = 500\text{GeV}$, $x_L = 0.1$ (b), respectively.

To see the maximum of the relative correction in the LHT model, we take $f = 500\text{GeV}$, $x_L = 0.1$ for the process $\gamma\gamma \rightarrow t\bar{t}$ in polarized photon collision mode. We show the dependance of the relative correction $\delta\sigma/\sigma$ on the center-of-mass energy \sqrt{s} and the third family mirror quark mass M_3 for the process $\gamma\gamma \rightarrow t\bar{t}$ with unpolarized and completely $+-, ++, --, -+$ polarized photon beams in Fig4.(a) and Fig4.(b), respectively. From Fig.4(a) and Fig.4(b) we can see clearly that the relative correction $\delta\sigma/\sigma$ in $--$ photon polarization collision mode are larger than in other photon collision modes. In $--$ photon polarization collision mode, the maximum of the relative correction can be expected to reach about -1% in the favorable parameter space.

V. CONCLUSIONS

In the framework of the LHT model, we studied the one-loop contributions of the T-odd particles to the top-quark pair production cross section in unpolarized and polarized photon collision modes. Because the contributions of the T^+, T^- change from negative to positive with the x_L increasing, in some cases the contribution of the third family mirror quark to the relative correction $\delta\sigma/\sigma$ was enhanced, and in other cases the contribution was counteracted. In all collision modes, we found that the relative correction $\delta\sigma/\sigma$ can be more significant in the $--$ polarized photon collision mode than in other collision

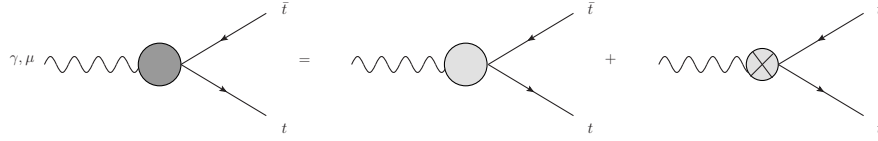
modes. In the favorable parameter space, the relative correction can be expected to reach about -1% .

Acknowledgments

We thank Cao Jun-jie for providing the calculation programs and thank Wu Lei for useful discussions. This work is supported by the National Natural Science Foundation of China under Grant Nos.10775039, 11075045, by Specialized Research Fund for the Doctoral Program of Higher Education under Grant No.20094104110001 and by HASTIT under Grant No.2009HASTIT004.

Appendix: The expression of the renormalization vertex $\hat{\Gamma}_{\gamma t\bar{t}}^\mu$ and the renormalization propagator $-i\hat{\Sigma}^f(p)$ [15]

(I) Renormalization vertex



$$\hat{\Gamma}_{\gamma t\bar{t}}^\mu = \Gamma_{\gamma t\bar{t}}^\mu - ieQ_t\gamma^\mu(\delta Z_V^t - \gamma_5\delta Z_A^t - \frac{S_W}{2C_W}\delta Z_{ZA}) + ie\gamma^\mu(v_t - a_t\gamma_5)\frac{1}{2}\delta Z_{ZA}$$

where

$$v_t \equiv \frac{I_t^3 - 2Q_t S_W^2}{2C_W S_W}, \quad a_t \equiv \frac{I_t^3}{2C_W S_W}, \quad I_t^3 = \frac{1}{2}, \quad Q_t = \frac{2}{3}$$

$$\delta Z_{ZA} = 2 \frac{\Sigma_T^{AZ}(0)}{M_{Z_L}^2}$$

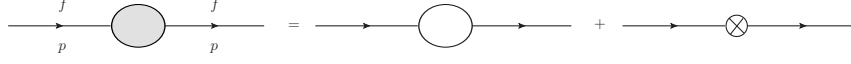
$$\delta Z_L^t = \text{Re}\Sigma_L^t(m_t^2) + m_t^2 \frac{\partial}{\partial P_t^2} \text{Re}[\Sigma_L^t(P_t^2) + \Sigma_R^t(P_t^2) + 2\Sigma_S^t(P_t^2)]|_{P_t^2=m_t^2}$$

$$\delta Z_R^t = \text{Re}\Sigma_R^t(m_t^2) + m_t^2 \frac{\partial}{\partial P_t^2} \text{Re}[\Sigma_L^t(P_t^2) + \Sigma_R^t(P_t^2) + 2\Sigma_S^t(P_t^2)]|_{P_t^2=m_t^2}$$

$$\delta Z_V^t = \frac{1}{2}(\delta Z_L^t + \delta Z_R^t), \delta Z_A^t = \frac{1}{2}(\delta Z_L^t - \delta Z_R^t)$$

$$\begin{aligned} \hat{\Gamma}_{\gamma t\bar{t}}^{LHT,\mu} = & \Gamma_{\gamma t\bar{t}}^\mu(\eta) + \Gamma_{\gamma t\bar{t}}^\mu(\omega^0) + \Gamma_{\gamma t\bar{t}}^\mu(\omega^\pm) + \Gamma_{\gamma t\bar{t}}^\mu(\pi^0) + \Gamma_{\gamma t\bar{t}}^\mu(h) \\ & + \Gamma_{\gamma t\bar{t}}^\mu(A_H) + \Gamma_{\gamma t\bar{t}}^\mu(Z_H) + \Gamma_{\gamma t\bar{t}}^\mu(W_H^\pm) + \Gamma_{\gamma t\bar{t}}^\mu(Z) + \Gamma_{\gamma t\bar{t}}^\mu(\omega^\pm, W_H^\pm) \\ & + \delta\Gamma_{\gamma t\bar{t}}^\mu(\eta) + \delta\Gamma_{\gamma t\bar{t}}^\mu(\omega^0) + \delta\Gamma_{\gamma t\bar{t}}^\mu(\omega^\pm) + \delta\Gamma_{\gamma t\bar{t}}^\mu(\pi^0) + \delta\Gamma_{\gamma t\bar{t}}^\mu(h) \\ & + \delta\Gamma_{\gamma t\bar{t}}^\mu(A_H) + \delta\Gamma_{\gamma t\bar{t}}^\mu(Z_H) + \delta\Gamma_{\gamma t\bar{t}}^\mu(W_H^\pm) + \delta\Gamma_{\gamma t\bar{t}}^\mu(Z) \end{aligned}$$

(II) Renormalization propagator



$$-i\hat{\Sigma}^f(p) = -i\Sigma^f(p) + (-i\delta\Sigma^f(p))$$

where

$$\begin{aligned}\Sigma^f(p) &= m_f \Sigma_S^f(p^2) + \not{p} P_L \Sigma_L^f(p^2) + \not{p} P_R \Sigma_R^f(p^2) \\ \delta\Sigma^f(p) &= \delta m_f + m_f \frac{1}{2} \delta Z_L^f + m_f \frac{1}{2} \delta Z_R^f - \not{p} P_L \delta Z_L^f - \not{p} P_R \delta Z_R^f \\ \delta m_f &= -m_f \text{Re}[\Sigma_S^f(m_f^2) + \frac{1}{2} \Sigma_L^f(m_f^2) + \frac{1}{2} \Sigma_R^f(m_f^2)] \\ \delta Z_L^f &= \text{Re} \Sigma_L^f(m_f^2) + m_f^2 \frac{\partial}{\partial p^2} \text{Re}[\Sigma_L^f(p^2) + \Sigma_R^f(p^2) + 2\Sigma_S^f(p^2)]|_{p^2=m_f^2} \\ \delta Z_R^f &= \text{Re} \Sigma_R^f(m_f^2) + m_f^2 \frac{\partial}{\partial p^2} \text{Re}[\Sigma_L^f(p^2) + \Sigma_R^f(p^2) + 2\Sigma_S^f(p^2)]|_{p^2=m_f^2}\end{aligned}$$

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